THE EFFECTS OF A LOWER BODY EXOSKELETON LOAD CARRIAGE ASSISTIVE DEVICE ON OXYGEN CONSUMPTION AND KINEMATICS DURING WALKING WITH LOADS

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ABSTRACT

The purpose of this study was to investigate the metabolic cost of wearing a prototype exoskeleton (EXO) while walking with a range of heavy loads, and to analyze the associated gait biomechanics. Ten Army enlisted men participated in the study. Oxygen consumption (VO_2) and gait biomechanics were measured while Soldiers walked at 4.83 km/h and 0% grade under three realistic load weight configurations that were comprised of Army clothing and equipment: fighting load (20 kg), approach march load (40 kg), and emergency approach march load (55 kg). The volunteers were tested under all load configurations with and without wearing the EXO prototype. Mean VO_2 significantly increased while wearing the EXO compared to not wearing the EXO across all conditions. Mean VO_2 scaled to body mass and scaled to total mass also significantly increased while wearing the EXO. Mean VO_2 and mean VO_2 scaled to body mass significantly increased with load, however, there were no significant EXO by load interaction effects for both the non-scaled and scaled VO_2. The kinematic and kinetic data revealed significant changes when wearing EXO compared to not wearing EXO. In summary, volunteers walked with shorter and faster strides; maintained a more flexed posture with reduced movement at the individual leg joints; braked with higher ground reaction forces at heel strike; and pushed off with lower force at toe off. This study demonstrated that use of an exoskeleton prototype increases users' metabolic cost while carrying various loads and alters their gait biomechanics compared to conventional load carriage using a backpack.

1. INTRODUCTION

Excessive loads continue to burden the dismounted Soldier. A recently released survey of the load weights being carried by infantry troops during operations in Afghanistan reported that, for 48 to 72-h missions, approach march loads in excess of 45 kg (100 lbs) were carried by Soldiers in some squad positions (Task Force Devil Combined Arms Assessment Team, 2003). Often, Soldiers are required to perform high-intensity, physical tasks immediately following a sustained march with these heavy loads. The rate of oxygen consumption (VO_2), an index of the metabolic cost of an activity, has been demonstrated to increase with the mass of the load carried (Sagiv et al., 1994; Soule et al., 1978). In addition, heavy loads have been found to increase energy cost over time and increase injury potential, both of which can reduce mission effectiveness through associated fatigue (Epstein et al., 1988; Knapik et al., 1992; Patton et al., 1991; Reynolds et al., 1990).

The Army is continually striving to reduce the weight of the load a Soldier must carry without compromising the Soldier's safety as well as the required mission capabilities. The development of wearable exoskeletal devices that are designed to bear the weight of a carried load and reduce the metabolic cost of heavy load carriage, therefore, is of great interest to the U.S. Army. A prototype of a lower extremity exoskeleton designed for this purpose has been purchased by the Army. The device consists of: 1) tubular leg struts that parallel the lateral surfaces of the wearer's legs and joints at the hip, knee and ankle; 2) semi-rigid foot plates that contain sensors to monitor contact with the ground and that have bindings to secure the user's shod feet; and 3) a hip structure with a back plate to which a backpack is attached. The prototype EXO is designed to reduce the vertical force component of the backpack load exerted on the wearer by the application of variable damping to its leg joints during locomotion that enables the transfer of force through the device to the ground.

Exoskeletons are a new technology and little is known about the extent to which carrying an external load with such a device affects metabolic cost and gait biomechanics. Even though the prototype EXO is designed to reduce a portion of the vertical component of the carried load that is exerted on the human, the device is not capable of producing any additional torque to raise the load against gravity or control the load in the anterior-posterior and medio-lateral directions. Therefore, the user must control the moment of inertia (MOI) of the carried load as well as generate the force necessary to propel the device forward even though the EXO stores and returns

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some energy during walking via springs in the hip and ankle joints.

The prototype EXO weighs approximately 15 kg and is worn primarily on the legs, with each EXO leg weighing approximately 3.18 kg. Studies of load added to the lower extremities have demonstrated that adding weight to the lower extremities results in a 5 to 10% increase in energy expenditure per 1.0 kg of added weight (Catlin & Dressendorfer, 1979; Claremont & Hall, 1988; Jones et al., 1986; Legg & Mahanty, 1986; Martin, 1985; Miller & Stamford, 1987). Further, not only does adding mass to the limb affect energy cost but how that mass is distributed over the limb can also have an effect on energy cost (Royer & Martin, 2005). Therefore, given the mass of the EXO as well as the placement of a substantial portion of its mass on the wearer's legs, the question as to whether the requirement for additional metabolic energy created by that mass is offset by the storage and return of mechanical energy from the springs in the ankle and hip joints and by any advantage imparted through the removal of a portion of the load's vertical force component on the wearer needs to be determined. Moreover, it is possible that any real metabolic advantage imparted by the EXO may be dependent on the magnitude of the load carried, such that the metabolic energy cost per unit mass becomes lower than non-EXO assisted load carriage only when heavy loads (greater than 50% of body mass) are carried by the device.

The purpose of this study was to investigate how the EXO affects the energy cost of load carriage and the associated gait biomechanics. The energy expenditure of individuals carrying militarily relevant loads while wearing and not wearing the device was examined using a measure of oxygen uptake and to analyze the associated gait biomechanics.

2. METHODS

Ten Army enlisted men of similar age (mean age=21 yrs) and size (mean height=1.76 m, mean body weight=75.3 kg) participated in the study, with nine completing all testing. Informed consent was obtained and the study was conducted in accordance with the provisions of Army Regulation 70-25 and 32 CFR Part 219. The participants had recently completed Infantry basic and advanced training, and were awaiting their first assignments to operational Army units. All volunteers were healthy and without musculoskeletal injuries or disorders.

2.1 Load Conditions

The volunteers were tested under three load conditions: a 20 kg fighting load (FL), a 40 kg approach load (AL), and a 55 kg emergency approach load (EAL). The fighting load was comprised of combat boots, socks, T-shirt, and spandex shorts, a mock M-4 weapon, body armor with miscellaneous equipment attached, and a helmet. The approach march and emergency approach march loads consisted of the fighting load plus a backpack (a MOLLE rucksack and frame) loaded with a mass of 20 kg and 35 kg, respectively (Fig. 1). Common Soldier items were used within the backpack and attached to the outside of the MOLLE in a typical Soldier load fashion to attain the desired weights. The backpack loads were configured such that the center of mass (COM) was approximately 0.22 m posterior to the back of the wearer and 0.25 m superior to the hips of the wearer. The total weight of the EXO was 15 kg, with the EXO legs weighing 3.18 kg each.

Fig. 1. Soldier wearing EXO prototype and approach load.

2.2 Testing Equipment

Oxygen uptake (VO_2) was measured using a ParvoMedics (Salt Lake City, UT) TrueMax 2400 metabolic measurement system, which monitors oxygen uptake, carbon dioxide production (VCO_2), and minute ventilation (V_E) and displays and prints the measures every 20 sec.

The force plate treadmill, fabricated by AMTI (Watertown, MA), was used for testing at 4.83 km/h (3.0 mph). This treadmill is comprised of two synchronized treadmills on a single platform and is capable of measuring ground reaction force in three planes. Each treadmill is mounted on its own force plate. The two treadmills are positioned very close together with the gap between the belts being less than 1.0 cm. The treadmill motors are linked and synchronized such that, as the speed of one treadmill's belt changes, the speed of the other belt automatically adjusts to match its speed. Data are sent from the force transducers in the treadmill to a dedicated computer, which also receives information about the treadmill speed and incline. The force plates instrumented in the treadmill can measure ground reaction forces in three planes. Each force plate in the treadmill provides six continuous voltage output signals corresponding to forces and torques in three orthogonal directions (x, y, z). All six output channels of each of the force transducers are connected via wires to the analog inputs of a dedicated computer. The voltages at each input channel were converted at the rate of 1200 Hz to digital values and stored in computer data files. Manufacturer provided calibration factors were used to convert the raw data into actual forces.

Three dimensional motion data were recorded by Motion Capture Unit (MCU) cameras (Qualisys Medical AB, Gothenburg, Sweden) as the volunteers walked on the treadmill. These data were used to analyze gait kinematics. Retro-reflective markers, approximately 19 mm in diameter, were placed at selected locations on the volunteer's skin and clothing (Fig. 2). To capture the volunteer's movements on the treadmill, eight cameras, operating at 120 Hz, were focused on the area of the treadmill. The cameras were positioned on each side and anterior and posterior to the viewing area. The camera placement allowed for the kinematics of the whole body to be defined in three-dimensional space.

The recorded images were processed using dedicated hardware and software (Qualisys Medical AB, Gothenburg, Sweden) to produce files containing time histories of the three-dimensional coordinates of each reflective marker. The Visual 3-D software program (C-motion Inc., Rockport, MD) was used to process the data files to produce histories of numerous kinematic and kinetic variables describing the volunteer's posture and gait.

2.3 Testing Procedures

Prior to testing, the EXO was sized for each volunteer ensuring that an acceptable fit was achieved as determined independently by an EXO engineer. Each volunteer then completed a total of 4-6 hours of familiarization and training with the EXO. During this training session, the volunteers became familiar with carrying each load while wearing the EXO while walking on the treadmill at 4.83 km/h (3 mph).

Fig. 2. Soldier wearing EXO prototype and fighting load with retro-reflective markers placed for motion capture collection.

All load conditions were tested both with and without wearing the EXO. The order of presentation of the load conditions and EXO was randomly assigned and based on a Latin square approach. EXO load conditions and No-EXO load conditions were tested on separate days approximately a week apart. Volunteers walked on the force-plate treadmill at 4.83 km/h at 0% grade for 8 minutes with each load configuration. During the fifth minute, 20 seconds of kinematic and kinetic data were collected. After six minutes on the treadmill, volunteers donned a nose clip and a head-mounted gas collection mouthpiece connected by a flexible hose to the ParvoMedics ® TrueOne 2400 gas analyzer. Measurements of VO_2 (ml/min) were collected breath-by-breath and averaged over 20-second increments for a period of 2 minutes. They were then ensemble averaged for the entire 2-minute gas collection period and that value was used in the analysis. After each load condition was completed, all load components were removed and the volunteer was allowed approximately 15 minutes to rest between test conditions.

2.4 Data Processing and Statistical Analysis

Statistical analyses were accomplished using SPSS 13.0. Collected VO_2 (ml/min) data were also scaled to both body mass (VO_2BM), by dividing VO_2 by the individual's body mass (kg), and to total mass (VO_2TM), by dividing VO_2 by body mass plus total added mass (all equipment, pack mass, plus EXO mass). Kinetic data were scaled to total mass, by dividing the ground reaction force data by body mass plus total added mass. For all kinetic and kinematic data, each dependent measure was calculated for the left and right sides during 5 strides that were selected for analysis. The kinematic and kinetic variables were then averaged over 5 strides, as well as across left and right sides, for a given test condition. A two-factor repeated measures analysis of variance (No-EXO/EXO, three load configurations) was run on each of the VO_2, kinetic, and kinematic variables. In all analyses in which the sphericity assumption was not met, the Greenhouse-Geisser adjustment was applied to the degrees of freedom. Alpha was set at .05. Each significant ANOVA finding was followed up with post-hoc tests adjusting for multiple comparisons with the Bonferroni method.

3. RESULTS

Mean values reflecting the main effects of EXO and load are listed for each dependent variable in Tables 1-5. Device means that do not share the same superscript differed significantly (p < .05) on the repeated measures ANOVAs; Load means that do not share the same superscript differed significantly (p < .05) on the Bonferroni post-hoc tests.

The metabolic cost data are summarized in Table 1. Mean VO_2 was significantly greater when using the EXO compared to No-EXO across all load conditions. Mean VO_2BM and mean VO_2TM also yielded statistically significant increases with EXO. VO_2 significantly increased with load, except when scaled to total body mass. There were no significant device by load interaction effects for VO_2, VO_2BM, and VO_2TM.

The temporal and distance data are summarized in Table 2. For temporal data, only double support time yielded a significant interaction effect of device by load condition (p < .05). Follow-up paired t-tests found an EXO/No-EXO effect for the AL and the EAL. For both loads, the double support time for EXO was shorter than for No-EXO (Fig. 3). In addition, for the No-EXO condition, double support time significantly increased as load increased. Main effects of temporal data revealed significant decreases in mean stride length and stance time when wearing EXO compared to not wearing EXO. In addition, mean step width was significantly greater while wearing the EXO compared to not wearing the EXO. With regard to the main effects of load, swing time was significantly greater for the FL compared to the AL and the EAL. However, the AL and the EAL were not significantly different.

Table 1. Means (and Standard Deviations) of the Metabolic Cost of Each Device Condition and Load at 0% Grade and a Walking Velocity of 4.83 km/h (N = 9)

	Device		Load		
DV	EXO	No-EXO	FL	AL	EAL
			(ml/min)		
VO_2	2427.2^A (281.6)	1515.4^B (207.2)	1742.7^A (448.6)	1921.2^B (479.5)	2250.3^C (525.2)
			(ml/min/kg)		
VO_2BM	32.7^A (5.3)	20.4^B (3.2)	23.5^A (6.5)	25.9^B (7.1)	30.3^C (7.8)
			(ml/min/kg)		
VO_2TM	19.1^A (1.7)	13.5^B (1.0)	16.8^A (3.3)	15.6^B (3.1)	16.3^A (3.1)

Table 2. Means (and Standard Deviations) of the Gait Variables for Each Device Condition and Load at 0% Grade and a Walking Velocity of 4.83 km/h (N = 9)

	Device		Load		
DV	EXO	No-EXO	FL	AL	EAL
Cycle Time (s)	1.08^A (0.05)	1.11^A (0.04)	1.10^A (0.04)	1.10^A (0.05)	1.09^A (0.06)
Dble. Supp. Time (s)	0.33^A (0.03)	0.35^B (0.04)	0.32^A (0.03)	0.35^B (0.03)	0.35^B (0.04)
Stance Time (s)	0.70^A (0.04)	0.73^B (0.03)	0.71^A (0.04)	0.72^A (0.03)	0.72^A (0.05)
Step Time (s)	0.54^A (0.03)	0.56^A (0.02)	0.55^A (0.02)	0.55^A (0.02)	0.55^A (0.03)
Step Width (m)	0.19^A (0.03)	0.15^B (0.03)	0.17^A (0.03)	0.17^A (0.04)	0.17^A (0.04)
Stride Length (m)	1.43^A (0.09)	1.49^B (0.07)	1.44^A (0.07)	1.47^A (0.08)	1.48^A (0.11)
Swing Time (s)	0.38^A (0.02)	0.38^A (0.07)	0.39^A (0.01)	0.38^B (0.02)	0.37^B (0.02)

The joint angle data for the ankle, knee, hip and trunk are presented in Tables 3 and 4. For total joint range of motion (ROM), only hip ROM yielded a significant interaction effect of device by load condition (p< .05). Follow-up paired t-tests found an EXO/No-EXO effect for the FL, where EXO hip ROM was greater than the No-EXO condition; however, no device effect was evident for the AL or the EAL. A load main effect was found for the No-EXO condition; hip ROM significantly increased as load increased. Main effects of ROM data revealed total joint ROM of the trunk, knee, and ankle

(Table 3) were significantly different when wearing the EXO. Trunk ROM was greater; however knee and ankle ROM were reduced. A load effect was found for ROM of the knee. EAL ROM was significantly smaller than the FL ROM; however, AL ROM was not significantly different from either the FL or EAL ROM.

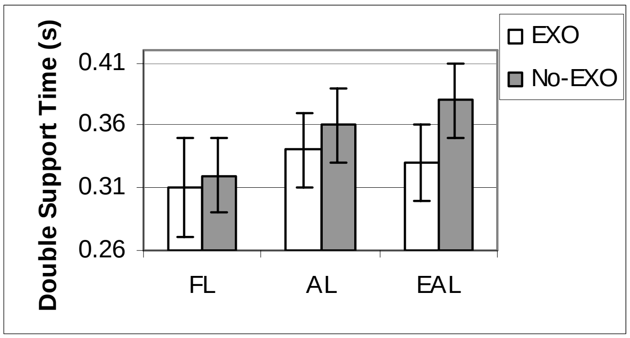

Fig. 3. Significant interaction effect of device x load for mean double support time. Error bars indicate 1 SD.

Mean trunk lean angle and mean maximum and minimum trunk, hip, knee, and ankle angles are displayed in Table 4. Mean trunk lean angle, maximum trunk lean and hip angles, and minimum trunk lean angle yielded a significant interaction effect of device by load condition ($p < .05$). Mean, maximum, and minimum trunk lean angle follow-up paired t-tests showed that as load increased trunk lean angle increased significantly for both EXO and No-EXO conditions; however, a device effect was not found for any of the three load conditions (Fig.4). Follow-up paired t-tests for maximum hip angle found an EXO/No-EXO effect for the FL, where the maximum hip angle for the EXO condition was greater than for the No-EXO condition; however, no device effect was found for the AL or EAL maximum hip angle. In addition paired t-tests indicated that maximum hip angle increased significantly as load increased for both device conditions. Main effects of maximum and minimum angle data revealed mean minimum hip angle to be significantly greater when wearing EXO compared to not wearing EXO and, as load increased, mean minimum hip angle significantly increased. Mean maximum knee angle for the EAL was significantly smaller than for the FL; however, the AL was not different than either the FL or the EAL. Mean minimum knee angle was found to be significantly greater while wearing the EXO compared to the No-EXO condition. Mean maximum ankle angle was significantly smaller and mean minimum ankle angle was significantly greater while wearing the EXO compared to the No-EXO condition.

Table 3. Means (and Standard Deviations) of Maximum Range of Motion (ROM) in Degrees of Each Joint During a Complete Stride (heel strike to heel strike) for Each Device Condition and Load at 0% Grade and a Walking Velocity of 4.83 km/h (N = 9)

	Device		Load		
DV	EXO	No-EXO	FL	AL	EAL
Trunk (deg)	5.5^{A} (1.4)	4.1^{B} (1.0)	4.5^{A} (1.8)	4.9^{A} (1.3)	5.0^{A} (0.9)
Hip (deg)	48.7^{A} (5.5)	48.2^{A} (6.3)	45.0^{A} (5.2)	48.6^{A} (5.3)	51.7^{B} (5.2)
Knee (deg)	62.9^{A} (6.3)	69.8^{B} (4.1)	68.6^{A} (6.6)	66.3^{AB} (5.1)	64.2^{B} (6.7)
Ankle (deg)	24.0^{A} (2.4)	29.4^{B} (2.4)	26.5^{A} (4.0)	27.0^{A} (3.2)	26.6^{A} (3.8)

Table 4. Means (and Standard Deviations) of Average, Maximum and Minimum Angles of Each Joint During a Complete Stride (heel strike to heel strike) for Each Device Condition and Load at 0% Grade and a Walking Velocity of 4.83 km/h (N = 9)

	Device		Load		
DV	EXO	No-EXO	FL	AL	EAL
Average Angle (deg)					
Trunk	13.7^{A} (7.3)	11.9^{B} (8.7)	3.1^{A} (3.5)	14.4^{B} (1.9)	21.1^{C} (2.9)
Maximum Angle (deg)					
Trunk	16.7^{A} (7.4)	14.1^{B} (9.0)	5.4^{A} (3.9)	17.0^{B} (2.3)	23.8^{C} (3.1)
Hip	55.7^{A} (7.8)	50.1^{B} (11.7)	41.6^{A} (6.8)	54.5^{B} (4.6)	62.5^{C} (4.6)
Knee	68.7^{A} (6.2)	69.9^{A} (5.6)	70.3^{A} (5.9)	69.4^{AB} (5.6)	68.2^{B} (6.3)
Ankle	12.0^{A} (2.9)	15.2^{B} (4.1)	13.4^{A} (4.0)	13.7^{A} (3.9)	13.7^{A} (3.9)
Minimum Angle (deg)					
Trunk	11.2^{A} (7.4)	10.0^{A} (8.5)	0.9^{A} (3.5)	12.1^{B} (1.8)	18.7^{C} (2.8)
Hip	6.9^{A} (8.1)	1.9^{B} (7.6)	-3.4^{A} (5.6)	5.8^{B} (5.2)	10.8^{C} (6.3)
Knee	5.7^{A} (4.0)	0.1^{B} (3.8)	1.7^{A} (6.1)	3.1^{A} (3.3)	4.0^{A} (4.6)
Ankle	-12.0^{A} (3.4)	-14.2^{B} (4.4)	-13.1^{A} (4.1)	-13.3^{A} (4.0)	-12.9^{A} (4.4)

Mean peak ground reaction forces (GRF) scaled to total mass (body mass plus total added mass of all equipment) and time to peak ground reaction forces as a percentage of stride are listed in Table 5. For peak GRF, only 1st peak vertical and peak medial forces yielded a

significant interaction effect of device by load condition ($p < 0.05$). Follow-up paired t-tests found an EXO/No-EXO effect individually at each load for both variables, with the EXO condition consistently resulting in greater 1st peak and medial forces. In addition for both variables, peak forces increased significantly with an increase in load while wearing the EXO. Main effects of mean peak GRF data revealed wearing the EXO resulted in smaller 2nd peak forces compared to not wearing the EXO. For the 2nd peak, the EAL peak force was significantly smaller than the FL and the AL peak force, which were not significantly different from each other. For the anterior-posterior peak forces, peak braking and peak propulsion, wearing the EXO resulted in significantly greater peak braking forces and significantly smaller peak propulsion forces compared to not wearing the EXO. For the peak braking force, the FL peak force was significantly smaller than both the AL and EAL peak force, which were not significantly different from each other. However, for the peak propulsion force, no load effect was evident. Peak lateral force was significantly less while wearing the EXO compared to not wearing the EXO. Peak lateral force showed a significant decrease as load increased.

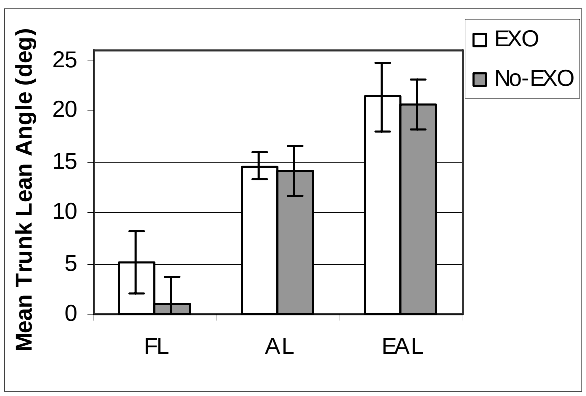

Fig. 4. Significant interaction effect of device x load for the means of mean trunk lean angle. Error bars indicate 1 SD.

As a percentage of stride, the time to 2nd peak vertical force and peak medial force yielded a significant interaction effect of device by load condition ($p < .05$). Follow-up paired t-tests on the time to 2nd peak vertical force found an EXO/No-EXO effect for the AL and the EAL, but not the FTL. The 2nd peak force consistently occurred sooner in the stride for the EXO compared to the No-EXO condition. In addition paired t-tests revealed that for the EXO condition, the time to the 2nd vertical peak for the EAL occurred significantly sooner than for the FL and for the No-EXO condition, the time to the 2nd vertical peak for the AL occurred significantly sooner than for the EAL. Follow-up paired t-tests on the time to peak medial force found an EXO/No-EXO effect individually at each load, with the peak force in the EXO condition consistently occurring sooner in the stride compared to the No-EXO condition. In addition for both the EXO and No-EXO conditions, the AL time to peak medial force was significantly different than the FL time to peak medial force, where for the EXO condition the AL time to peak medial force occurred sooner than the FL time to peak medial force, and for the No-EXO condition, the FL time to peak medial force occurred sooner than the AL time to peak medial force. Main effects of time to peak forces as a percentage of stride revealed the 1st peak vertical force and the peak propulsive force occurred sooner in the stride while wearing the EXO. There were no load effects for either variable. No device effect was found for peak lateral force as a percentage of stride; however, the EAL peak lateral force occurred significantly sooner than the FL and AL peak lateral force. The occurrence of the FL and Al peak lateral forces were not significantly different from each other.

Table 5. Means (and Standard Deviations) of Peak Ground Reaction Forces Scaled to Total Mass (TM) and Times to Peak Ground Reaction Forces for Each Device Condition at 0% Grade and a Walking Velocity of 4.83 km/h ($N = 9$)

	Device		Load		
DV	EXO	No-EXO	FL	AL	EAL
Peak Ground Reaction Forces (N/TM)					
1st Peak Vertical	12.7^{A} (0.7)	11.3^{B} (0.6)	11.6^{A} (0.7)	12.1^{B} (1.0)	12.3^{B} (1.1)
2nd Peak Vertical	9.9^{A} (0.5)	10.8^{B} (0.7)	10.5^{A} (0.8)	10.4^{A} (0.7)	10.1^{B} (0.8)
Peak Braking	-2.5^{A} (0.4)	-2.1^{B} (0.3)	-2.1^{A} (0.4)	-2.4^{B} (0.4)	-2.4^{B} (0.3)
Peak Propulsive	1.8^{A} (0.2)	2.1^{B} (0.2)	2.0^{A} (0.2)	1.9^{A} (0.2)	2.0^{A} (0.3)
Peak Medial	1.2^{A} (0.2)	0.6^{B} (0.1)	0.8^{A} (0.2)	1.0^{B} (0.4)	1.0^{B} (0.4)
Peak Lateral	0.3^{A} (0.2)	0.4^{B} (0.1)	0.5^{A} (0.1)	0.4^{B} (0.1)	0.3^{C} (0.1)
% of Stride at Peak Ground Reaction Forces					
1st Peak Vertical	13.4^{A} (0.9)	15.5^{B} (1.0)	14.7^{A} (1.3)	14.4^{A} (1.4)	14.2^{A} (1.4)
2nd Peak Vertical	47.5^{A} (1.8)	49.4^{B} (1.1)	48.9^{A} (0.9)	48.1^{A} (2.2)	48.3^{A} (1.9)
Peak Braking	11.3^{A} (1.5)	12.2^{A} (1.3)	12.0^{A} (1.7)	11.7^{A} (1.4)	11.5^{A} (1.3)
Peak Propulsive	54.2^{A} (1.5)	55.2^{B} (1.0)	54.6^{A} (1.1)	55.0^{A} (1.2)	54.5^{A} (1.7)
Peak Medial	14.6^{A} (1.5)	27.7^{B} (7.6)	20.2^{A} (7.9)	21.9^{A} (9.4)	21.4^{A} (8.7)
Peak Lateral	4.8^{A} (1.3)	4.1^{A} (1.0)	5.1^{A} (1.2)	4.4^{A} (1.1)	3.9^{B} (0.9)

4. DISCUSSION

The use of EXO significantly increased the metabolic cost of carrying a load. At the heaviest load (EAL), mean oxygen consumption scaled to body mass for the EXO condition was equal to 36.9 ml/min/kg (SD $\pm$ 4.86), which is approximately 71% of the mean maximum VO_2 capacity of Soldiers of a similar demographic (Epstein et al., 1988; Gordon et al., 1983; Santee et al., 2001;). According to Epstein et al. (1988), load carriage that requires a work intensity at greater than 50% of an individual's maximum VO_2 will lead to gradual further increases in energy cost over time as fatigue progresses. This continual increase in fatigue results in a necessary termination of the activity. In addition, tasks that require a VO_2BM of more than 28.3 ml/min/kg are classified as extremely heavy effort tasks and cannot be sustained for durations greater than 20 min by the majority of the potential work force (Eastman Kodak Company Staff, 1986). Therefore, the results of this study reveal that carrying a heavy load with the EXO is not metabolically sustainable for more than brief periods, even in Soldiers who are physically fit.

The additional mass of the EXO was directly responsible for a substantial portion of the increase in oxygen consumption with EXO. The work required to redirect and accelerate mass forward has been shown to comprise about one-half of the total metabolic cost of loaded walking (Grabowski et al., 2005). In addition, Grabowski et al. (2005) estimated that supporting body weight accounts for 28% of net metabolic cost of normal walking. While wearing the EXO, the user must support their own body weight together with some portion of the downward vertical force generated by the added load, suggesting that the work done to support the vertical load component still contributes to the overall metabolic cost when wearing the EXO. However, when oxygen consumption was scaled to total mass, an approximate 30% increase in EXO VO_2TM remained compared to No-EXO, indicating that the mass of the EXO was not the sole reason for the increased metabolic cost.

Load distribution of the EXO itself likely contributed to the increase in VO_2TM as well. Forty three percent (1.4 kg) of each EXO leg mass (3.18 kg), is located at the foot. Loads placed on the foot increase the weight, mass, and moment of inertia of the leg and require greater muscle activity to propagate leg swing. These factors have been shown to negatively affect oxygen consumption (Royer & Martin, 2005, Browning et al., 2004). Moreover, the moment of inertia of the entire system and the horizontal (anterior-posterior and medio-lateral) force components of the EXO carried load must be actively controlled by the user. Thus, the distribution of the EXO mass distal on the wearer's leg plus the need to control the inertia of the total mass also contributed to the 30% increase in VO_2TM seen with EXO

Inherent mechanical inefficiencies of the EXO (e.g. non-frictionless mechanical joints and mis-alignment with anatomical joints) may have also served to impede horizontal movement, alter gait kinematics and further contribute to increased oxygen consumption (Gottschall & Kram, 2003). The kinematic data revealed that volunteers overall took wider, shorter, and faster strides while maintaining a more flexed posture with reduced movement at the knee and angle joints while wearing the EXO compared to No-EXO load carriage. With the shorter and faster strides in wearing the EXO, double support time decreased, however, swing time remained unchanged.

At each load, the kinetic data revealed that the peak vertical and braking forces occurring at heel strike were increased when wearing the EXO. Across loads, however, vertical and propulsion forces occurring at toe off were decreased. Additionally across loads, peak lateral force was lower while wearing the EXO while peak medial force with the EXO was almost double that of peak medial force in the No-EXO condition and reached its peak in almost half the time. This supports the notion that managing the inertia of the increased mass of the EXO altered the normal forces produced by the wearer during walking. Specifically, it resulted in a greater challenge in generating propulsive force at push off and a marked increase in the braking force experienced at heel strike, both of which likely required increased muscular force to control thus contributing to the increase in VO_2TM with EXO. The use of electromyographic sensors placed on the muscles of the legs in future studies could be used to confirm this.

5. SUMMARY

The results of this study are specific to the prototype EXO tested. However, this study demonstrates that wearing an EXO to offload the vertical force component of a carried load does not necessarily compensate for the added mass and increased MOI of the EXO-human system in terms of achieving an overall reduction in the metabolic cost of load carrying. Exoskeletal devices as a whole must be lightweight, or feel lightweight to the user through gain control of actuation, and not interfere with normal gait kinematics in order to impart a metabolic benefit to the wearer. Additionally, the gait biomechanics that resulted from wearing the EXO reflected alterations in the movement and force generation patterns of the wearer that likely were responsible for offsetting any metabolic benefit imparted by the device. Although the tested device provided no torque generating capacity, future exoskeletons with powered actuators must provide

for control of the system's inertia and interface with the human wearer in such a manner as to minimize the effort required move with the system.

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